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A comparison of ground-based methods for estimating canopy closure for use in phenology research

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ABSTRACT

Climate change is influencing tree phenology, causing earlier and more prolonged canopy closure in temperate forests. Canopy closure is closely associated with understorey light, so shifts in its timing have wide-reaching consequences for ecological processes in the understorey. Widespread monitoring of forest canopies through time is needed to understand changes in light availability during spring in particular. Canopy openness, derived from hemispherical photography, has frequently been used as a proxy for understorey light. However, hemispherical photography is relatively resource intensive, so we tested a range of inexpensive alternatives for monitoring variability in canopy closure (visual estimation, canopy scope, smartphone photography, smartphone photography with fisheye attachment; and image analysis with specialist hemispherical photography software or with simpler, open access image analysis software). Smartphone photography with an inexpensive fisheye lens attachment proved the most reliable estimator of canopy closure. We found no significant difference in canopy estimations from three widely-owned smartphone models with differing resolutions and fields of view, and no significant effect of camera operator on the results. ImageJ, a free image analysis software, detected canopy variability in a similar way to HemiView specialist hemispherical photography software. We recommend a combination of smartphone photography with fisheye attachment and analysis with ImageJ for identifying changes in the timing of canopy closure (but not for estimating absolute canopy closure). We discuss how large-scale citizen science using this approach could generate meaningful and comparative data on the timings of canopy closure in different forests, year-to-year.

1. Introduction

Climate change is affecting forest ecosystems around the globe, with changes in tree phenology widely documented for temperate forests (Richardson et al., 2013; Roberts et al., 2015; Vitasse et al., 2011). Growing season extensions have been observed for many European tree species, most notably due to canopies coming into leaf earlier (Menzel and Fabian, 1999; Menzel et al., 2006; Thompson and Clark, 2008). The phenology of dominant canopy trees exerts strong influence on the understorey environment, as canopy openness is highly related to available photosynthetically active radiation (PAR) (Brusa and Bunker, 2014; Gonsamo et al., 2013; Promis et al., 2012), influencing microclimate, soil respiration (Giasson et al., 2013; Yuste et al., 2004) and understorey plant dynamics (Van Couwenberghe et al., 2011). Therefore, earlier canopy closure and later senescence is likely to have wide-ranging impacts on the phenology and life processes of understorey plants and wider forest biodiversity. Studies have indicated threats to spring ephemeral herbs that utilise the period before canopy closure for completing their life cycle (Kim et al., 2015). Many tree saplings depend on spring sunlight prior to canopy closure for their growth and survival (Augspurger, 2008). Understorey species that are shade tolerant or those with greater phenological plasticity are likely to gain competitive advantage (De Frenne et al., 2011), and invasive species could become more prevalent (Engelhardt and Anderson, 2011; Willis et al., 2010). As canopy openness is a key determinant of ecological processes in the understorey, effective methods for monitoring intra and inter-annual changes in the timing of canopy closure/openness would be very useful, especially if they allowed data to be collected across a variety of spatial scales, and with plenty of replication.

Canopy phenology has been extensively studied in recent years. Satellite remote sensing has enabled data collection of forest leaf phenology at large spatial scales (Boyd et al., 2011; Wang et al., 2016; White et al., 2009; Wu and Liu, 2013; Zhang et al., 2005). These methods focus on deriving estimates of canopy green-up dates from Normalised Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) data, for the purpose of tracking photosynthetic

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activity to assess forest productivity, gas exchange and phenological feedbacks to the climate system (Richardson et al., 2013). While remote sensing data is useful for identifying large-scale phenological trends, the coarse resolution means that local variations between forest stands are often masked (Fisher et al., 2006; White et al., 2014). Furthermore, loss of temporal resolution due to atmospheric conditions (Cleland et al., 2007; White et al., 2014), and difficulties separating greening of the understorey from canopy greening (Hamunyela et al., 2013), can compromise the use of this data for identifying shifts in canopy closure timing.

A range of ground-based methods have been used to assess canopy structure and understorey light environments at the forest-level. Direct measures of understorey light are highly affected by sky conditions and accurate determination requires continuous measurement over several days (Engelbrecht and Herz, 2001; Gendron et al., 1998). This makes direct measurements inappropriate for phenology studies where the objective is to assess variation through time. As an alternative, hemispherical photography and Plant Canopy Analysers (PCAs) such as the LAI-2200, are commonly used to assess structural attributes of forest canopies (Frazer et al., 1997; Gonsamo et al., 2013; Hale and Edwards, 2002; Rich, 1990). Both instruments incorporate an extreme wide angle view to measure gap fraction – defined as the proportion of unobstructed sky in a given region of the projected image plane (Frazer et al., 1997) – at multiple zenith angles. For estimating understorey light levels, particularly during spring, wide viewing angles are an advantage as sunlight largely penetrates the canopy below the zenith. Using gap fraction measurements, Leaf Area Index (LAI) and canopy openness can be determined.

LAI is the most widely used metric of canopy structure (Jonckheere et al., 2005; Weiss et al., 2004), though it is also one of the most difficult to characterise accurately (Bréda, 2003). LAI is defined as one half the total green leaf area per unit ground surface area (Chen and Black, 1992). Hemispherical photography and PCAs assess the whole canopy as viewed from a single point, using gap fraction inversion principles and radiative transfer theory respectively (Chen et al., 1997; Macfarlane et al., 2007; Woodgate et al., 2015). As such, LAI derived from optical methods actually characterises 'Plant Area Index' (as trunks and branches are included as well as leaves), and is highly related to understorey light levels (Bréda, 2003; Jonckheere et al., 2004). However, both methods are costly, particularly PCAs, which in addition to high instrument costs, require simultaneous reference light readings outside the canopy. This is problematic in forests, as a wireless set up or remote data loggers are needed, adding additional resource implications and making the method impractical for large-scale use (Bréda, 2003). Furthermore, both methods for estimating LAI assume that canopy elements are randomly distributed. In reality, a degree of 'clumping' occurs both within and between plant canopies (Bréda, 2003; Chen et al., 1997; Ryu et al., 2010; Weiss et al., 2004). The degree of clumping varies depending on forest type and structure, and also shows strong seasonal variation according to the phenological stage (Ryu et al., 2010). Therefore accurate LAI estimation requires determination of a clumping index for a given canopy at a given time of year, and specialist equipment and/or software is required (Chianucci et al., 2015; Ryu et al., 2010).

Digital Cover Photography (DCP) using ordinary digital cameras can also be used to estimate LAI following the method proposed by Macfarlane et al. (2007). This method has a number of advantages as specialist equipment and software are not required, though a number of steps are involved in analysis to calculate effects of foliage clumping (Chianucci et al., 2014; Macfarlane et al., 2007). DCP has been successfully used to track canopy development in phenological studies concerned with photosynthesis and gas exchange (Ryu et al., 2012). However, the restricted viewing angle of DCP cover photography is less appropriate for tracking the progress of canopy closure, where the objective is to assess change in the relative timing of shading in the understorey. Although LAI is highly related to understorey light (particularly where it is based on gap fraction at multiple zenith angles) it is primarily used to quantify ecosphysiological attributes of forest canopies (photosynthetic and transpiration rates) to study climate-biosphere interactions (Bréda, 2003; Chen et al., 1997; Jonckheere et al., 2004; Macfarlane et al., 2007; Woodgate et al., 2015). Where the aim is to track changes in relative canopy closure to determine temporal variability in understorey light, canopy openness is a more appropriate and straightforward metric to use (Brusa and Bunker, 2014).

Canopy openness is the proportion of the entire sky hemisphere that is unobstructed by vegetation when viewed from a single point (Jennings et al., 1999), and is highly correlated with understorey light (Brusa and Bunker, 2014; Gonsamo et al., 2013; Pellikka, 2001; Promis et al., 2012; Roxburgh and Kelly, 1995; Whitmore et al., 1993). Hemispherical photography has been widely used to assess canopy openness, representing the sum of all gap fraction values, weighted according to zenith angle, and multiplied by 100 to give a percent visible sky value (Frazer et al., 1997). The advent of digital cameras and their increasing availability has made hemispherical photography more widely available for forest science (Brusa and Bunker, 2014; Frazer et al., 2001; Hale and Edwards, 2002; Inoue et al., 2004). However, cost and resource implications still preclude many forest managers from using it as a monitoring tool. While hemispherical photography does not require reference light readings to be made, images must be taken under specific weather conditions – on dry, still days, without direct sunlight, normally early or late in the day, or on a day with uniform overcast skies (Rich, 1990). This places considerable constraint on when data can be collected. Once images have been obtained, analysis can be time-consuming and expensive. Though free specialist software programmes now exist that provide comparable results to professional software (Promis et al., 2011), expertise is still required. Overall, the technique is prohibitively expensive, in terms of cost and time, for phenology studies that require high levels of replication.

A variety of cost-effective, rapid assessment alternatives to hemispherical photography have been used to assess canopy openness, including photography without a fisheye lens (Pellikka, 2001), the canopy scope (Brown et al., 2000), and simple visual estimations (Jennings et al., 1999). These methods differ in their view zenith angle; therefore canopy openness in this context is defined as the proportion of unobstructed sky within the total area viewed. While these methods are used to characterise coarse-level variation in canopy openness, their ability to detect fine-scale changes in canopies through time needs to be assessed. Another option has emerged in the last few years with the rise of smartphones that have high resolution cameras. Inexpensive fisheye lens attachments for smartphones have recently become available for less than US$10. Smartphone photography, if reliable, could provide an efficient means of collecting large quantities of data on the timing of canopy closure using citizen science.

The use of citizen science has proven highly successful in other areas of phenological research, including observational studies of plant budburst and leaf-out timing (Collinson and Sparks, 2008; Jeong et al., 2013; Mayer, 2010). The widespread and increasing ownership of smartphones means that many people now carry sophisticated cameras, making them ideal citizen science tools. However, a considerable range of makes and models exist. These vary in their camera specifications (e.g. resolution, focussing capability and angle of view), which could affect canopy openness estimations (Frazer et al., 2001; Inoue et al., 2004; Jennings et al., 1999). Therefore, for this method to be practical for large-scale use, different makes and models of smartphone need to give comparable estimations.

In this study, we compared canopy openness values (% visible sky) from hemispherical photography, with estimates derived from visual estimation techniques and from smartphone photography, with and without the use of a fisheye lens attachment. Data were collected in winter, spring, summer and autumn, at fixed points across four broadleaved woodlands in south-west England, to assess the extent that surrogate methods can estimate variation in canopy openness. We then

tested a basic means of analysing hemispherical photos and smartphone fisheye photos to derive canopy openness using non-specialist image analysis software. We did this by comparing simple canopy openness values (% visible sky) derived from the free image-analysis software, with weighted canopy openness values (% visible sky weighted as a function of gap fraction zenith angle) from professional specialist software. Recognising that different makes of smartphone camera might perform differently, we also compared three popular smartphone cameras in a separate trial. The different phone cameras were tested in broadleaved woodland under three levels of canopy density, and with multiple camera operators, to test reproducibility under different canopy conditions and with different users.

Our overall objectives were: a) to identify whether any of the proposed surrogate methods provide reliable estimates of variation in canopy openness; b) to identify whether non-specialist image analysis software can produce comparable estimates to specialist software; c) to test whether different smartphone camera models and different camera users yield similar canopy openness estimations. It is important to note that this study was not concerned with identifying methods to closely represent absolute values, since it has already been established that methods incorporating different view angles tend to give different absolute estimates of canopy openness (Bunnell and Vales, 1990; Cook et al., 1995). Our focus was to identify whether any of the alternative methods could reliably identify relative differences in canopy openness to monitor canopy closure timings, and promote data collection through large-scale citizen science.

2. Methods

2.1. Comparison of methods against hemispherical photography

Trials took place in 2014 at four woodlands in Devon, England. The suite of sites was purposely chosen to represent a range of canopy/understorey light conditions, with varying aspect, composition and structure (Table 1). Six fixed sample points or 'stations' were randomly selected in each of the four woodlands. At each station, canopy openness was estimated by a variety of methods in each season (related to leaf phenology): winter (no canopy), spring (around 50% leaf-out), summer (full canopy) and autumn (around 50% leaf-drop). All estimates were made concurrently for a woodland within each season, and the four woodlands all estimated within a week of each other.

2.1.1. Hemispherical photography

Hemispherical photographs were taken in colour using a Nikon Coolpix 990 3.34 MP camera with Nikon Fisheye Converter FC-E8 lens (Nikon Corporation, Tokyo, Japan). The circular fisheye lens provides a 180° field of view in all directions. Images were taken using the basic quality setting and stored in VGA-size, as canopy openness estimates are not affected by resolution or size settings with this camera model (Inoue et al., 2004).

Photos were taken without rain or direct sunlight entering the lens (Rich, 1989). The camera was mounted on a tripod at 1.2 m above ground, and levelled using a circular bubble level. Pictures were taken using the camera timer function to reduce movement during image capture (Rich, 1989). Aperture and shutter settings were set to automatic, and to minimise error from over-exposure (Brusa and Bunker, 2014; Hale and Edwards, 2002), exposure was checked using the histogram function in the camera playback facility, following the method outlined by Beckschafer et al. (2013). Where over-exposure was apparent, exposure settings were manually lowered to -2.0 EV, the minimum limit on this camera.

Images were analysed in HemiView Canopy Analysis Software v.2.1 (Delta-T Devices, Cambridge, UK). The Coolpix 900 lens settings in HemiView were selected to correct for lens distortion (Hale and Edwards, 2002). Various options exist for classifying a photograph into "sky" and "not sky" (binarization), using image analysis software (Glatthorn and Beckschafer, 2014; Zhao and He, 2016). In HemiView, it is only possible to use manual thresholding of black and white pixels, so we followed this method, which has been widely used in other studies (Bertin et al., 2011; Capdevielle-Vargas et al., 2015; Hale and Edwards, 2002; Machado and Reich, 1999; Zhang et al., 2005). Each photograph was individually processed to obtain the best contrast between vegetation and the background sky, by visual comparison with the original photograph (Rich, 1990). A decision was made, based on visual assessment during threshold setting, whether each photo should be included in the analysis. If it was not possible to gain a good contrast between sky and vegetation across the whole image, that photo was excluded. Canopy openness—in HemiView, "% visible sky"— was then derived for each image by the software. In HemiView this value represents a weighted canopy openness score based on gap fraction zenith angles (Rich et al., 1999).

Following analysis in HemiView, photos were also analysed using ImageJ (Rueden et al., 2016). Photos were converted to 8-bit binary black ("not sky") and white ("sky") images in ImageJ. Following the same procedure as we used for photos in HemiView, the manual thresholding function in ImageJ was used to individually process each image and obtain the best contrast between vegetation and background sky. This was done with reference to the original photograph (Rich, 1990). Hemispherical photos consist of a circular image inside a rectangular frame. As ImageJ is not designed specifically for such images, it cannot automatically exclude the framing pixels as is possible in HemiView. Therefore to calculate canopy openness (the proportion of pixels classified as sky) excluding the frame, we first calculated the number of pixels in a reference image containing only open sky. We then used the 'batch measure function' to calculate white (sky) pixels for all images, and calculated the canopy openness as a proportion of the circular hemispherical image, excluding the framing pixels.

2.1.2. Smartphone photography with fisheye lens

Photos were taken using a Sony Xperia L smartphone camera (Android Version 5.0) with magnetic fisheye lens attachment (Skimn FE-12 180° fisheye lens). Images were taken at 5 MP using a 16:9 aspect ratio – the camera's default settings. Using these settings, the fisheye lens gave a 125° × 75° field of view. The smartphone was held level,

Table 1
Site descriptions of woodlands used to compare methods for estimating canopy openness. All sites were located in Devon, England.

Site	Size (ha)	Stand density (trees/ha)	Average tree height (m)	Aspect	Dominant canopy species	Dominant shrub layer species
Hardwick Wood (50°22'N, 4°4'W)	22	1360	16	Flat	*Acer pseudoplatanus, Fraxinus excelsior*	*Acer pseudeoplatanus, Ulmus* sp.
Hunshaw Wood (50°55'N, 4°7'W)	18	556	30	S	*Quercus robur* with *Fagus sylvatica* sub-canopy	*Corylus avellana, Sorbus aucuparia*
Newton Mill (50°52'N, 4°15'W)	25	456	35	NE	*Quercus robur*	*Corylus avellana, Fagus sylvatica*
Whitleigh Wood (50°25'N, 4°8'W)	20	1111	27	N	*Quercus robur* and *Betula pendula*	*Corylus avellana, Fagus sylvatica, Acer pseudoplatanus*

with the wider view orientated east-to-west when taking photos of the canopy, to ensure comparable images were obtained for each season. Photographs were taken in manual mode, with exposure lowered to −2.0 EV, the minimum limit on the camera. Images were stored as high quality JPEGs, between 2–3 MB in size.

Smartphone fisheye photos were analysed in HemiView and ImageJ and visible sky values were calculated, following the same procedures outlined for hemispherical photo analysis. Lens equation coefficients relating zenith angles and radial distance were calculated from a calibration curve constructed from measurements taken from reference photographs. The resulting lens correction function ($y = 1.2213x - 1.396x^2 + 1.0855x^3 - 0.2761x^4$) was used by HemiView to adjust the calculations to correct for lens distortion.

2.1.3. Smartphone photography without a fisheye lens

Smartphone photos were also taken of the canopy without the fisheye lens attachment, giving a 70° × 40° field of view. Photos were taken of the canopy directly overhead (with the wider view orientated east-west), and of the canopy facing in three different bearings from the station – at 60°, 180° and 300° (with the camera positioned in a landscape orientation at a at a 45° angle from the horizontal). All photos were taken using the same settings as the photos with fisheye lens attachment, and exposure settings were manually adjusted as previously described. Photographs were then analysed using ImageJ, following the same procedure for binarization, to derive a canopy openness estimation based on % visible sky. Two sets of canopy openness estimates were derived from these photos: one based solely on the overhead canopy photo, and one calculated as an average from all four photographs to incorporate a wider area of view.

2.1.4. Non-photographic methods

Canopy openness was estimated visually on a simple percentage scale. Two sets of canopy openness estimates were derived, one based solely on an overhead estimation, and another based on an average of four estimations: one directly overhead, and at three different bearings from the station (60°, 180° and 300°) at a 45° angle from the horizontal.

Brown et al. (2000) proposed a canopy scope to aid in the visual estimation of canopy openness. The scope consists of a simple Perspex sheet with a grid of twenty-five dots, spaced 3 cm apart in a 5 × 5 array. A 20 cm length of string is attached to the corner, and ensures the scope is held at a constant distance from the eyes when making estimations. Canopy openness was estimated by focussing the scope on the largest canopy gap visible from the station, and counting the number of dots coinciding with sky. This number was then multiplied by four to obtain a percentage estimate. Brown et al. (2000) found a close correlation between largest gap canopy openness and total canopy openness, but acknowledged that for woodlands with several similar sized canopy gaps, the largest gap estimate may not give an accurate representation. Two alternative estimates were made: one by pointing the canopy scope at the canopy directly overhead; and another by taking the mean of four canopy scope estimates (using the overhead estimate and estimates made from viewing the canopy at bearings of 60°, 180° and 300° from north, at an approximately 45° angle from the horizontal).

2.1.5. Statistical analysis

We used linear regression to compare canopy openness derived from hemispherical photographs in HemiView, against each surrogate method. We first compared data from all seasons and sites together to assess which methods were able to estimate broad changes in canopy openness. We then compared methods on a season-by-season basis across the four sites, to understand whether methods were capable of estimating finer-scale variation in canopy openness. We also conducted method comparisons on a site-by-site basis using data from all four seasons, to assess whether methods performed well across the different woodlands.

For methods that performed consistently well across the comparisons, Analysis of Covariance (ANCOVA) was used to test whether the methods estimated canopy openness in similar ways under different conditions, with seasons and sites as covariates. A Tukey-Kramer test was used to explore differences that were found between seasons or sites. All statistical analyses were carried out in R 3.3 (R Core Team, 2016).

2.2. Comparison of smartphone models and operators

2.2.1. Field imagery

A second trial comparing smartphone models and phone users took place in mixed deciduous woodland at Mount Edgcumbe Estate, Cornwall (approximately 50°35′N and 4°16′W), during summer when trees were in full leaf. Three sampling locations or 'stations' were selected at the site, using visual assessment, to represent a 'closed', 'intermediate' and 'open' overhead canopy. We tested two popular Smartphone cameras – the iPhone 5 and Samsung Galaxy S4 – against the Sony Xperia used in the previous trials, to assess the comparability of canopy openness estimates. Photos taken with the iPhone 5 had a resolution of 8 MP and an aspect ratio of 16:9, providing a 61° × 48° field of view. Photos taken with the Samsung Galaxy S4 had a resolution of 9.6 MP and aspect ratio of 16:9, providing a 57° × 34° field of view. Photos were stored as high quality JPEGS, between 2–3 MB in size.

Twenty-two volunteers consecutively took an overhead photograph of the canopy with each camera, at each of the three stations. All photos were taken within a half-hour period. Volunteers were instructed to hold the phone at an estimated level position and take a photo of the canopy above, but were not told to orientate the phone in a particular direction, as we were interested to see the extent that individual user operation affected consistency in the results. Photos were analysed in ImageJ following the procedure outlined above.

2.2.2. Statistical analysis

The Aligned Rank Transform (ART) procedure in the R package ARTool (Kay and Wobbrock, 2016), followed by separate ANOVA using R 3.3 (R Core Team, 2016), was used to assess the effects of phone user, phone model and canopy treatment on canopy openness values. The ART procedure is an appropriate way to analyse datasets which are not normally distributed, and is described in more detail by Wobbrock et al. (2011). We performed *post hoc* contrasts using estimated marginal means with the emmeans package (Lenth, 2017).

3. Results

3.1. Hemispherical photography with HemiView v other methods

All hemispherical photos taken were suitably exposed in relation to sky conditions, for inclusion in the analysis, while four smartphone fisheye photos and six smartphone photos without the fisheye lens attachment were eliminated due to overexposure, out of 96 photos in each case.

Analysis of hemispherical photography with ImageJ produced reliable estimates of canopy openness values derived from analysis with HemiView (Table 2, Figs. 1A and 1D). With photos from spring, summer and autumn combined into a single ANCOVA analysis, the slope of the relationship was no different for all three seasons (Fig. 1D ANCOVA $F_{2,66} = 2.55$, $p = 0.09$). However, the intercepts of the relationships were significantly different (Fig. 1D ANCOVA $F_{2,68} = 8.09$, $p < 0.001$), with summer values estimated relatively lower than those of spring and autumn (Tukey-Kramer Test, summer v spring $p = 0.004$, summer v autumn $p < 0.001$, spring v autumn $p = 0.864$).

None of the other methods closely estimated absolute canopy openness values derived from hemispherical photography, but all smartphone photographic methods reliably estimated relative

Table 2
Proportion of variation explained (R^2) and statistical significance (p) for relationships between hemispherical photography analysed with HemiView and alternative methods. Relationships were considered separately for each season, as well as across all seasons together.

Method	All seasons		Spring		Summer		Autumn		Winter	
	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p
Hemispherical photo (ImageJ)	0.96	< 0.001	0.85	< 0.001	0.77	< 0.001	0.94	< 0.001	0.69	< 0.001
Smartphone fisheye photo (HemiView)	0.89	< 0.001	0.83	< 0.001	0.67	< 0.001	0.79	< 0.001	0.05	0.300
Smartphone fisheye photo (ImageJ)	0.84	< 0.001	0.74	< 0.001	0.76	< 0.001	0.66	< 0.001	0.08	0.170
Smartphone photo (overhead)	0.85	< 0.001	0.57	0.002	0.43	< 0.001	0.69	< 0.001	0.04	0.380
Smartphone photo (average of 4)	0.81	< 0.001	0.15	0.410	0.60	< 0.001	0.72	< 0.001	0.02	0.490
Canopy scope (overhead)	0.51	< 0.001	0.24	0.240	0.01	0.170	0.41	< 0.001	0.00	0.820
Canopy scope (largest gap)	0.52	< 0.001	0.2	0.029	0.20	0.030	0.33	0.003	0.00	0.850
Canopy scope (average of 4)	0.55	< 0.001	0.31	0.005	0.18	0.040	0.55	< 0.001	0.00	0.910
Visual estimation (overhead)	0.39	< 0.001	0.01	0.740	0.05	0.280	0.31	0.005	0.06	0.260
Visual estimation (average of 4)	0.52	< 0.001	0.03	0.460	0.20	0.029	0.51	< 0.001	0.04	0.350

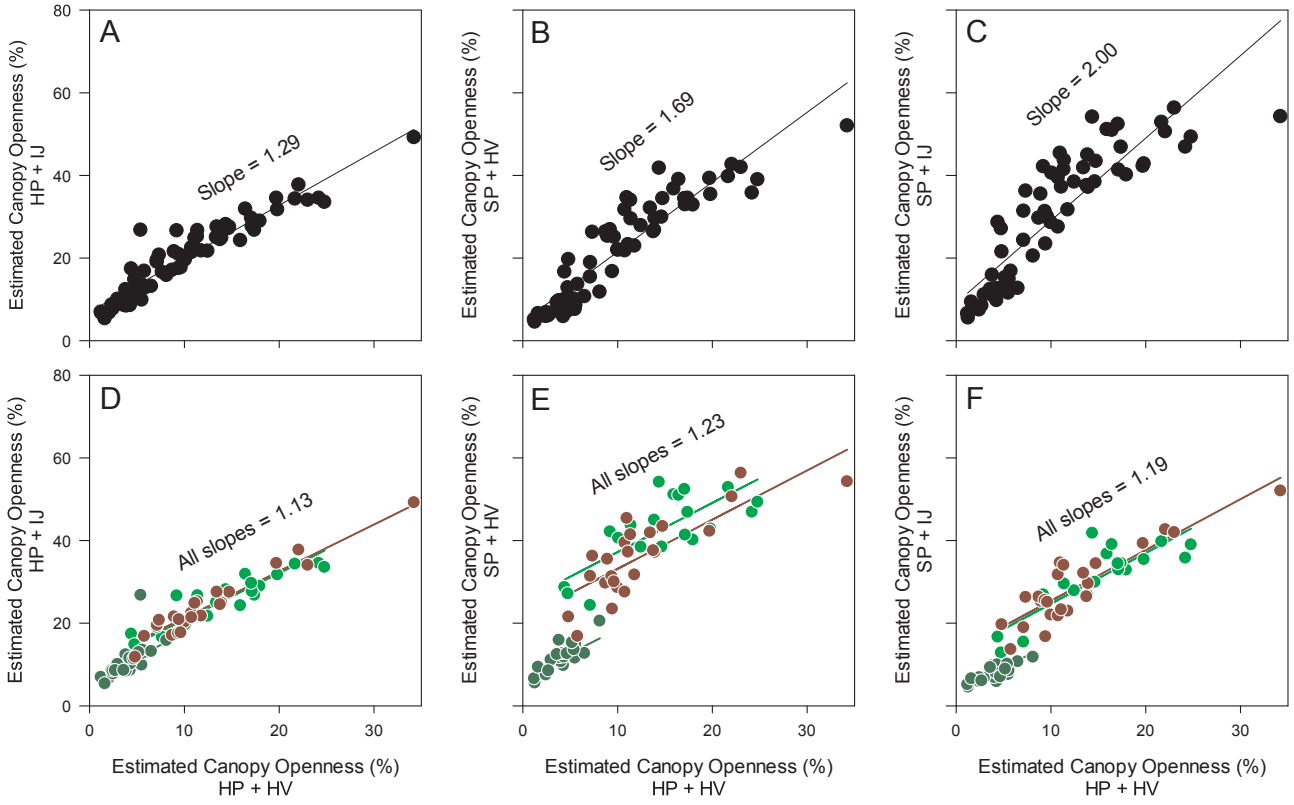

Fig. 1. Canopy openness estimates from hemispherical photography with HemiView (HP + HV) compared with estimates from hemispherical photography with ImageJ (HP + IJ), smartphone fisheye photography with HemiView (SP + HV), and smartphone fisheye photography with ImageJ (SP + IJ). Figs. A–C. Overall relationships across all seasons. R^2 and statistical significance of these relationships is presented in Table 2. Figs. D–F. Separate relationships for each growing season (light green = spring, dark green = summer, dark red = autumn) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

differences in canopy openness across all seasons for all sites (Table 2, Fig. 1B and C). The slopes of these relationships, which were all > 1, indicate that smartphone fisheye photography results in higher estimates of canopy openness than hemispherical photography, and that the estimates differ more at higher values of canopy openness. During winter, when there were very high levels of canopy openness (*mean* = 37%, *sd* = 5%), smartphone fisheye photos did not correspond reliably to hemispherical photography (Table 2). This was also true for all other methods tested, and since winter is not a season where canopy change is expected and therefore not relevant to our aims, winter data were excluded from the rest of the analyses. Non-photographic methods (canopy scope and simple visual estimations) were much poorer estimators of change in canopy openness across all seasons and sites (Table 2).

Smartphone with fisheye lens estimates taken in different seasons had similar slope relationships (Fig. 1E ANCOVA $F_{2,66} = 0.31$, $p = 0.73$; Fig. 1F $F_{2,66} = 0.64$, $p = 0.53$), but they varied in intercept (Fig 1E, ANCOVA $F_{2,64} = 33.56$, $p < 0.001$; Fig. 1F $F_{2,64} = 48.73$, $p < 0.001$). For smartphone photographs analysed with HemiView canopy analysis software, spring and autumn intercepts were not significantly different (Tukey-Kramer $p = 0.796$), but both were significantly different from summer ($p < 0.001$ in each case). The same photographs analysed with ImageJ had different intercepts for each of the three seasons (spring v autumn $p = 0.020$, spring v summer $p < 0.001$, summer v autumn $p < 0.001$).

Since smartphone fisheye photography and ImageJ analysis reliably estimated variation in canopy openness, we tested whether the methods performed consistently between different sites (Fig. 2). Hemispherical

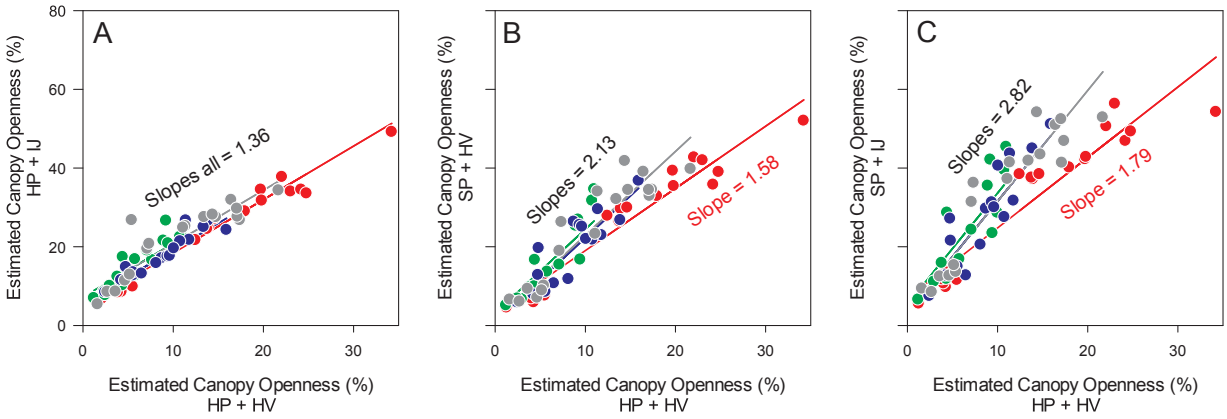

Fig. 2. Site canopy openness estimates from hemispherical photography with HemiView (HP + HV) compared with estimates from (A) hemispherical photography with ImageJ (HP + IJ), (B) smartphone fisheye photography with HemiView (SP + HV), and (C) smartphone fisheye photography with ImageJ (SP + IJ). R^2 and statistical significance of these relationships is presented in Table 3. Relationships are shown for each site (red = Hardwick, green = Hunshaw, blue = Newton Mill, grey = Whitleigh) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 3
Proportion of variation explained (R^2) and statistical significance (p) for relationships at each woodland site between estimates of canopy openness from hemispherical photography analysed with HemiView versus estimates from other methods. Photographs were included from spring, summer and autumn, but not winter.

Method	Hardwick		Hunshaw		Newton Mill		Whitleigh	
	R^2	p	R^2	p	R^2	p	R^2	p
Hemispherical photo (ImageJ)	0.97	< 0.001	0.85	< 0.001	0.98	< 0.001	0.81	< 0.001
Smartphone photo fisheye (HemiView)	0.95	< 0.001	0.86	< 0.001	0.86	< 0.001	0.86	< 0.001
Smartphone photo fisheye (ImageJ)	0.84	< 0.001	0.80	< 0.001	0.81	< 0.001	0.86	< 0.001
Smartphone photo (overhead)	0.88	< 0.001	0.78	< 0.001	0.68	< 0.001	0.85	< 0.001
Smartphone photo (average of 4)	0.92	< 0.001	0.93	< 0.001	0.70	< 0.001	0.85	< 0.001
Canopy scope (overhead)	0.47	0.002	0.08	0.260	0.68	< 0.001	0.19	0.072
Canopy scope (largest gap)	0.42	0.004	0.22	0.049	0.73	< 0.001	0.12	0.160
Canopy scope (average of 4)	0.39	0.005	0.25	0.034	0.75	< 0.001	0.16	0.100
Visual estimation (overhead)	0.42	0.004	0.1	0.200	0.60	< 0.001	0.01	0.630
Visual estimation (average 4)	0.47	0.002	0.2	0.063	0.67	< 0.001	0.01	0.740

imagery analysed with ImageJ showed similar slope relationships across all sites (Fig. 2A; ANCOVA $F_{3,64} = 1.17$, $p = 0.33$), but significant differences in intercept (ANCOVA $F_{3,67} = 4.75$, $p = 0.005$). The intercept of Hardwick was different from Hunshaw and Whitleigh (Tukey-Kramer Test, $p = 0.018$ and $p = 0.007$), though all other intercepts were not different ($p = 0.288$ to 1.000).

Smartphone with fisheye photography, whether analysed with HemiView or ImageJ, resulted in different slope relationships for Hardwick compared to the other sites (Fig. 2B, ANCOVA $F_{3,60} = 4.10$, $p = 0.010$; Fig. 2C, $F_{3,60} = 7.07$, $p < 0.001$). As canopy openness increased, the estimates for Hardwick differed less from the hemispherical standard than the other sites. The intercepts of the other sites did not differ (Fig. 2B, ANCOVA $F_{2,46} = 0.91$, $p = 0.41$; Fig. 2C, $F_{2,46} = 0.54$, $p = 0.59$).

3.2. Comparison of smartphone models and operators

The three canopy treatments (closed, intermediate and open) were clearly different from each other in terms of canopy openness, but it did not matter which phone model or user took the photos (Fig. 3; Aligned Rank Transform + ANOVA, $p_{\text{canopy}} < 0.0001$, $p_{\text{user}} = 1.00$ and $p_{\text{model}} = 0.50$). However, variability in estimation of canopy openness increased markedly as canopy openness increased. For the closed canopy, standard deviations of the estimates ranged from 0.79–1.46% canopy openness, but were much greater for the open canopy (7.42–12.43%).

4. Discussion

Our results showed that smartphone photographic methods estimated variation in canopy closure effectively, but rapid visual

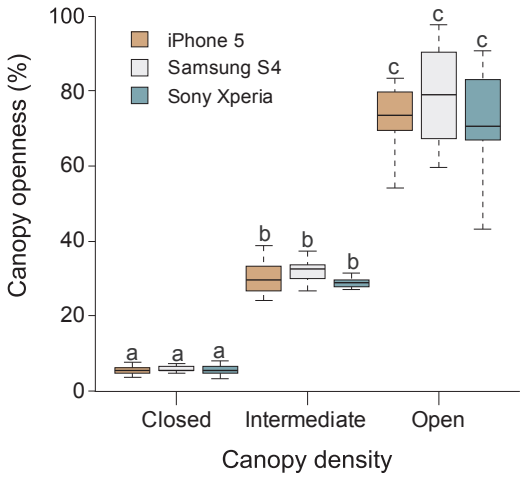

Fig. 3. Comparison of estimates of canopy openness using three different models of smartphone in three canopy densities. Every canopy density x phone combination was based on 22 photographs, each taken by a different user. The median is shown as a horizontal line, the box represents values within the 25–75% quartiles, and the error bars show the minimum and maximum values. Means sharing a letter were not significantly different according to *post hoc* contrasts using estimated marginal means.

estimation methods did not. Basic visual estimations of canopies are known to lack consistency, varying considerably due to weather conditions (Jennings et al., 1999) and observer biases (Vales and Bunnell, 1988). The canopy scope is more a quantitative visual estimation method, allowing for greater consistency and has been shown to have low between-observer bias (Brown et al., 2000), so is potentially more suitable for citizen science. However, while the canopy scope can distinguish quite different degrees of canopy openness (Brown et al., 2000), it lacked the fine resolution needed to distinguish between similar canopies, and therefore is less suitable for monitoring changes through time.

Smartphone photographic methods have now become a cost effective and practical alternative to visual estimation. Simple photographs using a smartphone camera without a lens attachment were sufficient for assessing the degree of variation in canopies across a whole season, but did not pick up fine-scale variations (i.e. between similar canopies within a season) compared with hemispherical photography. This is unsurprising, as their narrow angle of view means they are essentially providing an estimate of canopy cover directly overhead, as opposed to canopy closure across a range of zenith angles (Chianucci et al., 2014; Jennings et al., 1999). With the addition of an inexpensive fisheye lens attachment, smartphone photographs were able to pick up finer variations in canopy openness in spring, summer and autumn, which would be important for monitoring seasonal dynamics.

As anticipated, smartphone fisheye photography gave higher canopy openness estimations than hemispherical photography, due to its narrower field of view. With hemispherical photography, an image taken within a forest will typically include a ring of tree trunks and shrubs around the periphery, with low gap fractions in the outer portions of the image (at larger zenith angles) (Chen et al., 1997). Although incorporating a greater field of view than non-fisheye photos, smartphone fisheye photos still omit the largest zenith angles containing most of the lower trunks and shrub layer. In its field of view, the gaps in a canopy contribute more to the overall image. Similarly, twigs and foliage have higher prominence in images. As smartphone fisheye photography misses gaps at larger zenith angles, it would not be a suitable method for detailed studies of canopy structure or plant growth. However, the method is suitable for monitoring timing of canopy closure, and its narrower field of view could actually make it a superior method for identifying leafing activity early in spring.

We found canopy structure affected the relationship between hemispherical photography and smartphone photography, meaning that canopy openness values must be converted to proportions of total canopy closure to be correctly interpreted. Where the overhead canopy was uniformly closed, the difference between canopy openness estimations from smartphone fisheye photos and hemispherical photos was lower – both sets of images show a closed canopy with few gaps. In more open situations, the difference between the two sets of estimations was greater. Similarly where stand density was higher and the height of the tree canopy was lower (e.g. at Hardwick Wood, Table 1), the difference between canopy openness values from the two methods was smaller. Canopy height is known to effect openness estimations when the field of view is reduced (Jennings et al., 1999; Pellikka, 2001).

Due to the influence of canopy structure on canopy openness values, we propose this method is appropriate for monitoring relative change in canopies through time. In order to compare the timing and rate of canopy closure across different forest locations we can standardize along a proportional scale of canopy closure, where 0% represents the winter canopy value prior to budburst, and 100% represents the summer canopy value once the canopy is fully in leaf. We note that canopies are dynamic, and small-scale fluctuations occur through summer. Therefore the summer canopy value would be determined from the point where the canopy reaches 'adjustment stability' (Margalef, 1969), after which only small changes of less than 2% canopy closure are observed. The progress of canopy closure can then be plotted through time from 0–100%, and a logistic growth model can be fitted to characterise the phenological pattern (Richardson et al., 2006; Zhang et al., 2003). An example using smartphone fish-eye photography is provided in Supplementary Material.

In terms of photo analysis, we found that ImageJ is a reasonable alternative to professional specialist software such as HemiView, for deriving relative canopy openness values. It is clear that ImageJ overestimates values from HemiView to some degree, so again, this method would not be suitable for studies where absolute values were needed. The distortion of a hemispherical or fisheye lens causes the central part of the image, towards the zenith, to appear larger than peripheral elements towards the horizon (Herbert, 1987). Canopy openness derived from HemiView is based on a weighted gap fraction that takes into account the zenith angle of canopy gaps, and corrects for a given lens distortion (Promis et al., 2011). In contrast, canopy openness derived from ImageJ is simply the percentage visible sky across the image. However, values from ImageJ still consistently and reliably estimated relative differences in canopy openness in our study.

ImageJ has the benefits of being free, open access and relatively straightforward to use. It is not necessary to provide specifications of the fisheye lens to use it. Image binarization is still required, which can be time consuming. The manual thresholding technique used in this study would not be suitable for analysing large quantities of citizen science data. Many citizen science projects have successfully utilised internet crowd-sourcing applications (Kosmala et al., 2016) to involve the public in processing and classifying large numbers of images, so a similar approach could be used to binarize canopy photos, with multiple people classifying pixels for the same image to reduce error (Inoue et al., 2011). However, new methods for automatic thresholding of photos would improve efficiency (Brusa and Bunker, 2014; Glatthorn and Beckschafer, 2014; Inoue et al., 2004), and auto-thresholding plugins for ImageJ (Glatthorn and Beckschafer, 2014) could provide a viable option.

In terms of practicalities, smartphone fisheye photography is suitable for widespread use as part of citizen science projects, and if managed properly is a game-changer in terms of data quantity. The good agreement between smartphone models and users suggests the method can be reliably applied by citizen scientists. The three phone models tested varied in resolution and field of view, but still produced comparable results. While some variation was evident between photos taken with the same phone, under the same canopy conditions, there was no overall effect of phone user on canopy openness values. Variation between photos taken with the same phone was greatest at higher levels of canopy openness. This is not surprising, as under the dense canopy, gaps were small and uniformly distributed, whereas the open canopy comprised a very large central gap bordered by canopy. Small variation in camera positioning could therefore result in compositional differences between photographs. This could lead to significant differences in estimates, as has been observed with other methods for estimating canopy openness (Jennings et al. 1999). Therefore, we recommend that for best results camera position is standardised by installation of fixed camera mounts (University of New Hampshire, 2017) for citizen scientists to place their smartphones on in order to take repeat photographs of particular parts of the canopy.

The quality of photos obtained from smartphone fisheye photography is sufficient to obtain reliable data. The high resolution available with smartphone cameras is a clear advantage. Resolution is known to be an important factor influencing the quality of canopy openness measures from hemispherical photography (Brusa and Bunker, 2014; Woodgate et al., 2015), and in this study the smartphone camera resolution was superior to that of the hemispherical camera (with nearly 2,000,000 more pixels). It has also been noted that higher resolution images are less vulnerable to thresholding errors during image processing and analysis (Macfarlane et al., 2007). Some blurring was evident towards the perimeter of the smartphone fisheye photos, but this is also apparent with hemispherical photos (Frazer et al., 2001). Blurring from motion caused by holding the camera to capture images

could also influence image quality (Woodgate et al., 2015). The use of fixed mounts for phone cameras would help alleviate this problem, as well as utilising the camera's timer function or earphone controls to remotely operate the camera shutter.

As with hemispherical photography, there are several logistical issues associated with the use of smartphone photography, relating to sky conditions and image exposure. The effects of over-exposure and the importance of taking photos under uniform sky conditions has been emphasised in many studies (Beckschafer et al., 2013; Brusa and Bunker, 2014; Rich, 1990; Woodgate et al., 2015; Zhang et al., 2005). In this study, a small proportion of smartphone photos had to be excluded due to over-exposure. While smartphone photographs were taken at −2.0 EV, the lowest exposure setting available, Beckschafer et al. (2013) showed that over-exposure can still occur at −2.0 EV under bright skies. This can also be a problem with hemispherical photography, as the Nikon Coolpix 990 had the same limits for exposure compensation. The histogram function allows a definitive check as to whether photos are over-exposed, and more advanced cameras allow for lowering below −2.0 EV (Beckschafer et al., 2013). We emphasise again that the smartphone fish-eye photography method would not be suitable for detailed studies of canopy structure or growth where small differences between sites must be detected, and therefore consistent exposure is paramount (Leblanc, 2005). However, to track the progress of canopy closure through time and compare trends in the timing of this phenological event over large spatial scales, a small degree of noise in the data is acceptable. The example in Supplementary Material demonstrates that the phenological process of canopy closure can be clearly modelled using this method. While the limits of exposure settings on smartphone cameras may mean some photos have to be discarded, the greater number of images obtained by utilising a citizen science approach should increase the number of suitable images that can be included in a study. Where possible citizen scientists should be encouraged to take photos early or late in the day, which is when sky conditions are generally most appropriate, and coincides with times when people are likely to be available to collect imagery.

5. Conclusions

Smartphone fisheye photography, with relatively simple image analysis, offers a practical method for comparing changes in the timing of canopy closure across different forests year on year, and may even be more suited to this task than hemispherical photography. Using this approach, trends in proportional changes in canopy closure could be identified across different spatial and temporal scales using citizen science. Further research is required to assess the temporal resolution of image capture needed to represent canopy changes adequately.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.01.002

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